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Energy efficiency evaluation of zero energy houses

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ABSTRACT

Given the global energy and environmental situation, the European Union has been issuing directives with increasingly demanding requirements in term of the energy efficiency in buildings. The international competition of sustainable houses, Solar Decathlon Europe (SDE), is aligned with these European objectives. SDE houses are low energy solar buildings that must reach the near to zero energy houses' goal. In the 2012 edition, in order to emphasize its significance, the Energy Efficiency Contest was added. SDE houses' interior comfort, functioning and energy performance is monitored. The monitoring data can give an idea about the efficiency of the houses. However, a jury comprised by international experts is responsible for carrying out the houses energy efficiency evaluation. Passive strategies and houses services are analyzed. Additionally, the jury's assessment has been compared with the behavior of the houses during the monitoring period. Comparative studies make emphasis on the energy aspects, houses functioning and their interior comfort. Conclusions include thoughts related with the evaluation process, the results of the comparative studies and suggestions for the next competitions.

1. Introduction

The term efficiency is generally defined as the relation between the materials, energy or resources need to perform a task or provide a service, and the final result. Energy efficiency improvement is regarded as any action undertaken by a producer or consumer of energy products that reduce energy use per unit of output, without affecting the level of service provided [1]. Energy efficiency can be accomplished in three different ways: "requiring less energy to achieve the same result", "requiring the same amount of energy to produce a better result" and "requiring less energy to produce a better result". In order to reduce the environmental impact of the energy sector, it is necessary to minimize the requirements of energy and to increase the energy efficiency and the use of renewable energy. In addition to the environmental benefits, the energy efficiency also has significant economic and competitiveness advantages, permiting to reduce the external energy dependence. Additionally, most of the energy efficiency measures have short payback periods and ultimately add to bottom line profits as continued increases in the price of the energy [2].

In 2005, the European Union set out its political position regarding the energy efficiency in the Green Paper on energy efficiency, this document established the necessity of doing more with less energy [3]. In the same line in 2006, the European Union published its strategy for a reliable, competitive and sustainable energy support and the action plan for energy efficiency [4,5]. Building sector has a high potential of improvement in term of its energy consumption. Being aware of this, the European Union has issued directives in which it is required that the Member States takes major steps to increase their buildings energy-efficiency. In 2002, it issued the first Energy Performance of Buildings Directive (EPBD) and in 2010 approved the recast EPBD [6,7]. These directives emphasized the need to reduce the energy requirements and increase the energy efficiency of both new and existing buildings. In the 2002 EPBD, it was included the use of renewable energy, but the recast one has gone beyond, introducing the near to zero energy building (ZEB) concept. Near to ZEB is very high energy performance building that requires a very low amount of energy, and their energy requirements are covered to a very large extent by energy coming from renewable sources. The ZEB definition states, as pre-requisite, that the building is a low energy one. Most of the building energy consumption is related with the maintenance of hydrothermal and lighting comfort. As shown in Fig. 1, a low energy building needs first to reduce its energy requirements, responding adequately to its environmental conditions, having an appropriated envelope and

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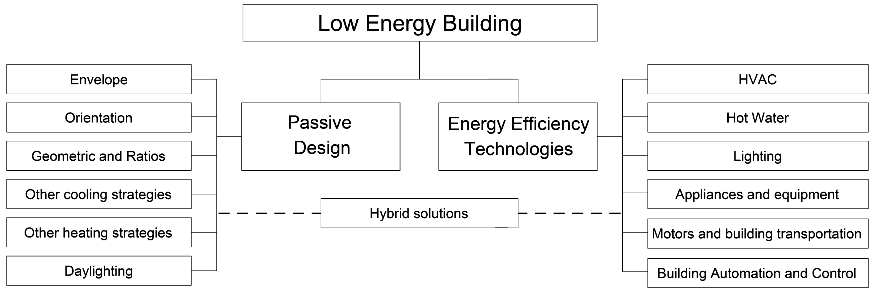


Fig. 1. Low energy buildings.

using passive design strategies. Furthermore, high energy efficiency systems and equipment need to be selected.

Solar Decathlon Europe (SDE) is an international competition based on the U.S. Department of Energy Solar Decathlon and created through an agreement between the Spanish and United States Government. In this competition, universities from all over the world are challenged to design, build and operate sustainable zero energy houses [8–11]. Participating houses are grid-connected and use the sun as the only source of renewable energy. During the competition final phase, each team assembles their house in Madrid, at the Solar Village. The final phase includes houses exhibition, public visits and the competition weeks. As part of the competition, the houses participate in ten contests, reason why the Competition takes the name of Decathlon. SDE has an objective to impulse the research, education and social awareness in relation to the responsible use of the energy, the use of renewable energy as well as the environment.

Since the beginning, following the objectives of the European Directives, the Solar Decathlon Europe encourage the participating Teams to develop a highly efficient solutions. SDE houses must be designed and equipped with technologies that permit the maximum energy efficiency. Participating houses are challenged to reach the level of zero energy houses; its performance in term of functioning, their capacity of maintaining a strict level of comfort conditions and the energy consumption is monitored continuously, during twelve days [12]. Certainly, the energy efficiency is a key factor of the SDE. The houses energy efficiency was part of the Engineering jury assessment, and it had a crucial influence in the results of the Energy Balance Contest. However, in the Solar Decathlon there was not a contest in which the energy efficiency was specifically assessed, not in the United States or Europe. In the SDE 2012, "Energy Efficiency Contest" was introduced for the first time. In this contest, the energy efficiency of the participating houses is evaluated for a jury constituted by three international experts. This new contest was added having two principal objectives: focus students' attention on efficient solutions, and raise public awareness about the significance of the energy efficiency. In this paper the evaluation of the energy efficiency of zero energy buildings is analyzed, using the SDE 2012 houses as case studies and having the following main objectives:

- Present passive and active strategies and solutions used by the houses, to obtain a high energy efficiency level.
- Explain the energy efficient jury base of assessment and the results.
- Compare the jury evaluation with the results of the monitoring at the competition final phase.

Additionally, an analysis related to the zero energy buildings possibilities has been also included. A double analysis was carried out: one, using the monitored results of consumption and production in the competition and another using the predicted annual consumption and production.

Since the energy efficiency is directly related to the houses comfort conditions and their functioning, for this work, it has been selected the fifteen SDE 2012 houses that obtained at least a 70% of the points in the Comfort Conditions and House Functioning contests. Three houses did not comply with these criteria. These houses were not finished in the SDE short assemble time. They were not able to enter in the competition from the beginning; some of their system were not complete set up or did not function correctly.

The present study has been organized as follows: Section 2 presents the energy efficiency in the context of the Solar Decathlon Europe. In Section 3, the participating houses high efficient solutions are explained. Houses performance during the competition is presented in Section 4. Section 5 focuses on the Energy Efficiency Jury evaluation. Comparative study between energy efficiency assessment and houses' performance in other related contest is presented in Section 6. Finally, conclusions are expounded in Section 7.

2. Energy efficiency in the context of the Solar Decathlon Europe

2.1. Solar Decathlon Europe contests

In Solar Decathlon Europe (SDE) there are some aspects that are not evaluated in the DOE Solar Decathlon. Also, in the SDE there was an evolution between the contests of the 2010 and 2012 competitions. SDE 2012 consists of 10 separately scored contests: Architecture, Engineering and Construction, Energy Efficiency, Energy Balance, Comfort Conditions, House Functioning, Communication and Social Awareness, Industrialization and Market viability, Sustainability and Innovation. There are prizes for each of these categories and the team with the highest total points at the end of the competition wins the competition.

Three contests, Energy Balance, Comfort Conditions and House Functioning, consist of several sub-contests and different assessment criteria. These contests assessment is based on the houses' monitored performance and the competition tasks completion. During the whole completion, an SDE organizer, called Observer, is in each house taking note of the results of the tasks carried out and observing that the teams compete following the SDE rules. For the monitored sub-contests, the SDE 2012 organization developed an instrumentation and data collection system. This system permits to know the performance of the houses in real time. All the data obtained by the SDE 2012 monitoring system is freely shared in the SDE Web (www.sdeurope.org). The data collection, scoring and visualization systems were custom designed for the SDE 2012 by the Technical University of Madrid (UPM) [12]. The data collector system manages the data from the power meters and all the houses sensors that are connected to a Programmable Logic Controller (PLC). This system has three main modules: control module, carrier module (to handle peripheral devices) and backup module.

The other seven contests are juried contest. Six juries, each one composed by three international experts, evaluate one particular aspect of the house plus the innovation in their area of evaluation. For the innovation punctuation, the assessment of all six juries is taken into account. Juries use their experience and knowledge in the evaluation of the houses, following the guidelines developed by the SDE Organization. This evaluation has four phases: documentation review, on-site evaluation, deliberation and scoring justification. The documentation review gives to the juries the opportunity to study the projects and to be prepared for the on-site evaluation. Juries have a chance to verify the proposed solutions during their visits to the houses. Also during the houses visits, the students give them explanations and answer their questions [10].

2.2. Energy Efficiency Contest

Energy efficiency is one of the juried contests. The objective of this contest is to encourage the right decisions in term of house design, services equipment and appliances, in order to maintain the interior comfort and the function of the houses with the minimum use of energy. As was explained in Section 1, low energy buildings approach start with the design solutions that minimize the energy demand, and also include the right selection of active systems and equipment (see Fig. 1). The Energy Efficiency jury bases its evaluation on the study of the houses' documentation (constructions drawings and project manual) as well as the visit of the houses and the teams explanations.

The documentation of houses includes complete information about the houses materials, strategies and systems; it also includes annual thermal and energy analysis. Teams carried out two different thermal and energy simulations: one using their local context conditions and another with the monitored period conditions. The monitored period simulations for the SDE 2012 took into account the environmental conditions of Madrid and the requirements of the competition. These analysis and simulations help the team to be prepared for the competition final phase. On the other hand, the analysis and simulations in their local context are used for the jury to evaluate the houses energy efficiency in the house permanent location.

The SDE organization ask the jury to evaluate the energy efficiency in the houses, focus on the house's envelope, passive or mostly passive systems, active systems (HVAC, lighting and hot water), energy analysis and estimated annual consumption, appliances selection, and control systems. In energy analysis of the house, the jury looks for the effective communication and synthesis of the team's design decisions and analysis process, as well as the correct application of engineering principles and how the simulations influence the improvement of the definitive house design. Additionally, innovative solutions are assessed positively.

2.3. Relation between the energy efficiency and other SDE 2012 contests

The ten SDE contests and the way to be assessed are clearly defined in the SED 2012 Rules [10]. Most of these contests are interrelated. Energy Efficiency Contest is related with other juried and monitored contests. These related contests were used as part of the comparative study between Energy Efficiency Jury assessment and houses' performance, see Section 6.

Energy efficiency is mostly related with the three juried contests: Architecture, Engineering and Construction and Sustainability. As for the Energy Efficiency Jury, SDE rules required that the Architectural Jury take into account aspects as the passive design strategies. The Engineer Jury must include in their evaluation the house envelope as well as the systems selected (hot water, lighting, etc.). Finally, the Sustainability Jury assess the aspects related to the bioclimatic solutions and energy issues.

Furthermore, the energy consumption of houses is mainly related to two purposes: to maintain the interior comfort conditions and keep the house functioning. An energy efficiency house must fulfill these objectives with minimum energy consumption. In the SDE 2012, the three monitored contest are related with the following objectives: Comfort Conditions, House Functioning and Energy Balance. Since the SDE houses are all-electrical houses, the contest is called "Electrical Energy Balance". Fig. 2 shows the sub-contests included in each one of them. In the next sections, this contest will be explained, and areas related with the houses energy efficiency will be highlighted.

2.3.1. Comfort Conditions Contest

The objective of this contest is to assess the capacity to provide and maintain interior comfort conditions. As shown in Fig. 2, the Comfort Conditions Contest includes several sub-tests, but for this analysis only those which may require the consumption of energy were used: interior temperatures, relative humidity, air quality and the lighting level. From this point on, the terms "Interior Comfort" and "Comfort Conditions", do not include the Airborne Sound Insulation test results.

Dry bulb temperature sensors measure constantly the interior temperature. There were two temperature sensors in each house, installed in poles at 150 cm from the fishing floor level. These sensors were placed at the center of the living areas and bedrooms. The SDE 2012 monitoring period was from September 17th to September 28th. SDE states that the teams earn points when the interior temperature is between 20 and 28 °C, obtaining the maximum punctuation in measurement between 23 and to 25 °C, as shown in Fig. 3a. Humidity sensors were located next to the temperature ones, and the relative humidity was also constantly measured. The maximum punctuation is obtained maintaining the humidity levels between 40% and 55%. The Fig. 3b shows the relative humidity sub-contest points distribution.

An CO_2 sensor is located in a tripod at the center of the living area, permitting continuous monitoring of the air quality. All available points are earned by keeping the content in CO2 below 800 ppm, and reduced points are earned if the content in CO_2 is between 800 ppm and 1200 ppm. There was also a luminance meter placed in the house workplace. All available points are earned at the conclusion of each scored period by keeping the lighting level above 500 lux during the scored period. Reduced points are earned if the lighting level is between 300 lux and 500 lux. Reduced point values are scaled linearly.

For the first time in SDE, during the 2012 competition, there was a singular period of 56 continuous hours, called "Passive Monitored Period". During this period, nothing in terms of monitoring or punctuations change, but the Teams can use only passive systems or strategies to maintain the interior comfort. For the purposes of the SDE, "passive" means any strategy or system that not relying is the function on a "thermodynamic cycle" or devices that do not have an internal production of heat or cold. Semi-passive or hybrid systems that used small pumps and fans were permitted. However, the use of electrical heaters, chillers (air conditioner), heat pumps or other equipment that include a thermodynamic cycle was not allowed during this period.

2.3.2. House Functioning Contest

In this contest, the functioning of the houses and their appliances are evaluated. As shown in Fig. 2, the House Functioning Contest has ten sub contests. This sub-contest tries to simulate the demanding standards of present day society, reproducing the intensive energy use of contemporary home. Teams earned the

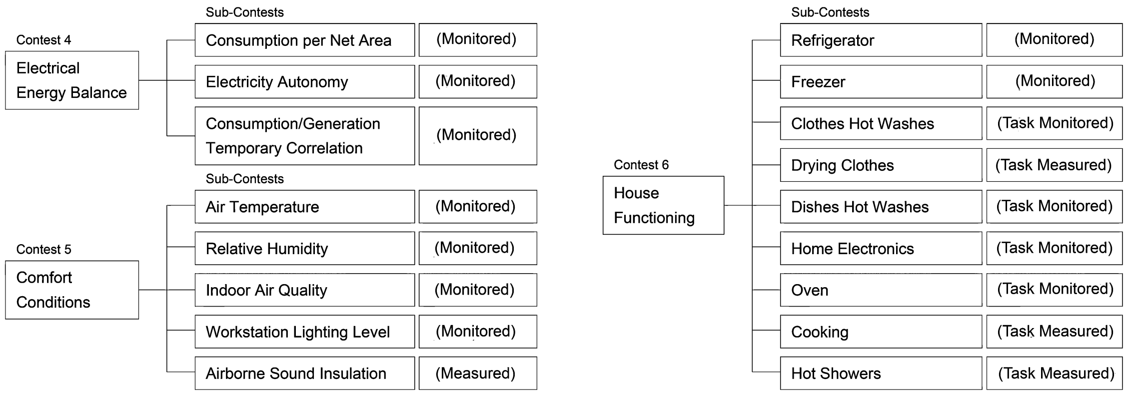


Fig. 2. SDE contests evaluated by continuous monitoring, punctual measurements and tasks completion.

points completing the tasks as indicated in the Competition Calendar, and complied with the requirements stated in the SDE 2012 Rules. The selection of high efficiency equipment and appliances, and use them correctly during the competition, help Teams to get high scores in both House Functioning and Electrical Energy Balance contests. ctly, help the teams to get points in the House Functioning contest, and also in the Electrical Energy Balance.

3. Participant houses solutions to get a high energy efficiency performance

Energy efficient buildings are able to maintain the interior comfort and provide the necessary services with minimum energy use, in a cost-effective and environmentally sensitive manner [13]. In order to achieve that, it is fundamental to select the right building envelope, use appropriated passive strategies and to install high efficient active conditioning systems, lighting and other required equipment. The correct selection of strategies, systems and equipment start with the complete understanding of the local environmental conditions.

However, SDE is an international competition. In the SDE 2012, teams participated from all over the whole world. There were houses from many European countries as well as from Asia and South America. The houses came from latitudes between 55.7° North and 22.5° South.

This point out to one of the challenges of the Organizer of the Competition, how evaluate houses from very different local conditions. In order to assess the houses performance in their local context SDE Organization look for international experts.

In order to get good results, also in the monitored contests, teams studied the environmental conditions of the competition site and made adjustments to their houses accordingly. Some of them clearly explain, in their documentation, the solutions or system added to the house, in order to respond adequately to the completion conditions. In the next section, solutions adequate to Madrid are explained.

3.1. *Adequate solutions for the competition on-site evaluation*

The performance of SDE 2012 houses was evaluated in Madrid. This city is located in the 40.24° N latitude at the center of the Iberian Peninsula. Madrid is at 667 m above sea level. It has continental mediterranean climate, characterized by cold winters and hot summers. Dry air, clear skies, high solar radiation and high diurnal thermal swings are common characteristics of its climate. It is a high peninsula.

CIBSE in one of its guide states as principles for energy efficiency to keep energy demand to a minimum through careful design of built form and services using renewable energy sources, ambient energy and passive solutions [13]. In the following paragraphs, the passive solutions and the participating teams' efforts to take advantage of the ambient energy and to reduce the necessity of active systems are explained, centered in those solutions suitable for the Madrid environmental conditions.

3.1.1. *SDE 2012 houses' envelope and passive strategies*

SDE 2012 teams, in general, selected very high performance envelope [14]. Additionally most of them work to provide an air-tight construction. Fig. 4 shows the walls and windows thermal transmittance (*U* value) of the fifteen houses of this study, as well as their glazing Solar Heat Gain Factor (*g* value).

In addition to the house envelopes, there are other strategies to accomplish a high energy efficiency performance. Parasonis [15] noted that manipulation of the form of building alters its energy use value, even though the physical characteristics of the envelopes remain unchanged. He also noted that architectural solutions and

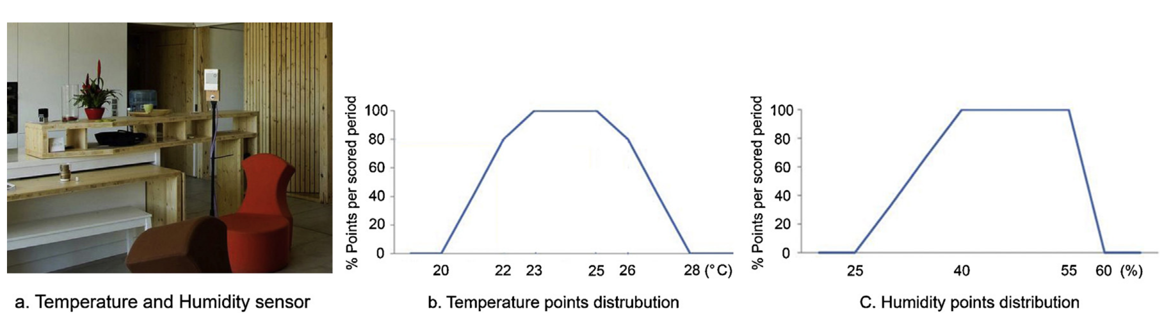


Fig. 3. Temperature and humidity sensors and sub-contests points distribution.

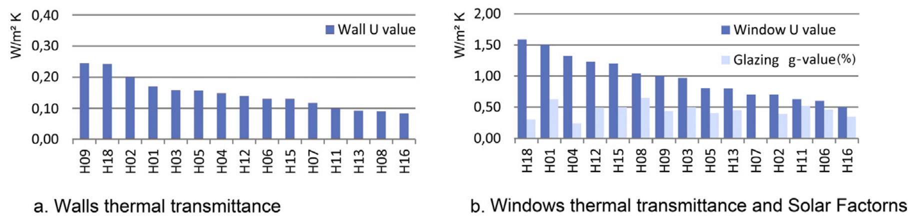


Fig. 4. Walls and windows thermal transmittance and glazing solar factor [14].

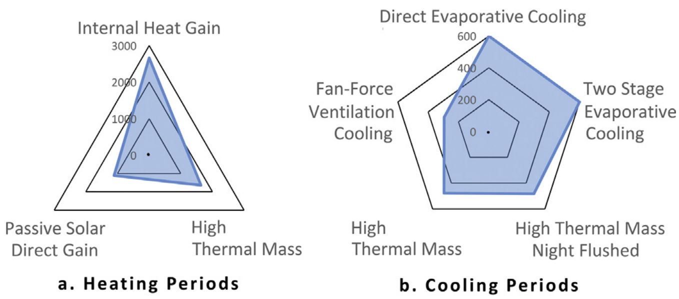


Fig. 5. Madrid: strategies for heating and cooling periods (potential number of hours that might be added to the hydrothermal comfort).

the volume of a building can be used to achieve greater energy efficiency for the entire lifecycle of the building [16]. These ideas are commented by Givoni many years ago, in relation to the passive system or solutions. The ability of a building to save energy, aside from its envelope materials, depends on its shape, orientation, layout of transparent envelopes, size, measures of protection from the sun, and the facade color [17].

In locations as Madrid, it is needed to develop appropriate strategies for both heating and the cooling periods. A psychometric analysis brings a rough estimation on the potential impact of the use of passive or hybrid solutions. Climate Consultant software permits to rank the strategies using the number of hours that can potentially be added to the comfort [18]. These number of hours represent just estimation; the final result will depend on building design, and how the suggested solutions are implemented. However, this tool helps to identify the appropriated strategies for a specific location. Fig. 5 shows the results of the psychometric analysis carried out by Rodriguez-Ubinas et al. [19] for Madrid City, using the comfort model defined in the 2005 ASHRAE Handbook of Fundamentals. The heating and cooling periods are presented in two radar figures, indicating the potential of hour that might be added to the comfort. For heating periods, internal gains, high thermal mass and direct solar gains were the principal passive strategies. And for the cooling periods, in addition to the solar protection, evaporative cooling, high thermal mass, thermal mass with night ventilation and fan force ventilation were the identified strategies.

Table 1 summarizes the passive, hybrid and active solutions used by the SDE 2012 houses. The strategies detected in the psychometric analysis are present in most of the houses. The passive strategies utilized are the base for the high efficiency performance of most of the houses. A detailed study about the SDE2012 houses was carried out by Rodriguez-Ubinas et al. [14].

It's high radiation points out the opportunity to take advantage of the direct and indirect solar gains in heating periods, and provide adequate solar protections during the cooling ones. Madrid's altitudes, and its dry climate, provoke high diurnal temperature swings that are more significant during summer. The high daily thermal swing enables the use of thermal energy storage (TES). The use of thermal mass and other TES helps to smoothen the interior temperature, and permit to reduce the necessity of mechanical conditioning. The Madrid's psychometric analyst, as shown in Fig. 5, recommend the use of TES for both heating and cooling periods. Fig. 6a–d shows the number of houses using TES. Seventeen of the eighteen participating houses use some kind of TES application. Some of them have Sensible TES systems based on heavy materials as concrete, stone or sand while others used Latent TES systems taking advance of the thermal storage capacity of phase change materials (PCM). From the SD 2005 in Washington, many Solar Decathlon houses had used Latent TES systems [20]. In 2012, 61% of the houses used the PCM passive or active applications.

Evaporative cooling and night sky radiant cooling systems can be appropriate strategies due the Madrid dry air, and clear skies [21]. Fig. 6e–h shows the quantity of houses that use these hybrid solutions. This figure also gives information about low temperature radiant surfaces and ventilation system with heat recovery. Most of the houses use different types of heat pumps, with two exceptions H13 and H18, see Table 1 and Fig. 6. These houses only use passive and hybrid systems. In relation of the DHW systems, only two houses do not use solar thermal systems. These houses use only heat pumps for the DHW.

4. SDE 2012 monitored period

4.1. Competition weeks' environmental conditions

In order to understand the performance of the participating houses during the SDE 2012 competition weeks, it is necessary to know the weather conditions during the monitored period. The SDE 2012 monitored period was from 17th to 28th September 2012. The Fig. 7 shows the climatic conditions of the measured period; the first six days had a climate conditions typical of the Madrid late summer and last six days presented temperatures of the beginning of autumn temperatures, with cloudy skies, high humidity and some rain.

4.2. Monitored period limitations and value of the jury assessment

SDE organization has developed a robust and reliable instrumentation, monitoring and visualization system. During the monitoring period, this system permits to know the houses performance in relation to the appliances use, comfort conditions as well as their electrical energy production, storage and consumption. However, the energy efficiency of the participating houses must not be evaluated taking into account only the monitoring period, since:

- The houses are designed for environmental conditions that are different to the competition site. In some cases, the differences are greater than in others.

Table 1
SDE 2012 houses passive strategies and other energy efficiency solutions.

House	H01	H02	H03	H04	H05	H06	H07	H08	H09	H10	H11	H12	H13	H14	H15	H16	H17	H18
Passive Strategies																		
Low Thermal transmittance	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Outside (or In/Out) insulation	■	■		■	■	■	■	■	■	■	■	■	■		■	■		
Air tightness	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Ventilated facade		■	■			■	■	■	■				■					
High performance glazing	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■
Multifunction facade		■									■							
Envelope over spaces' thermal envelopes																		■
Passive solar direct gain	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Sunspace (glass balcony, glass terrace)		■														■		■
Double skin glass facade																■		
Solar shading	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Roof shaded	■								■	■		■	■		■	■	■	■
Green roof	■																	
Natural ventilation	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Ventilation using stack or Ventury effect	■				■									■	■	■		■
Foyer or entrance vestibule					■									■		■		
Living areas south oriented	■		■	■	■		■	■	■		■	■	■	■	■	■		
Interior buffer zone(s)	■				■			■	■		■					■		
Patio		■	■									■			■			
Attached covered spaces	■	■		■	■	■	■	■			■		■		■	■		■
Pond(s)/planted wetland		■					■			▼	■				■		■	
Vegetation				■			■	■	■			■		■	■		■	
Thermal Energy Storage (TES)																		
Sensible TES in floor/walls/partitions	■		■		■	■						■		■			■	
Sensible TES unit (Tank/Deposit/Bed)			■					■		▼	■	■	■		■		■	■
PCM in ceiling/wall/floor/furniture		▼					■		■	▼	■				■		■	
PCM Storage unit	■					■							■			■		
Hybrid systems																		
Mobile solar shading	■	■	■	■									■	■				
Mechanical ventilation w/heat recovery	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■
Mechanical (cooling) night ventilation	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■
Ventilation (PCM heat exchange)	■															■		
Evaporative cooling	■	■	■	■			■		■				■		■		■	■
Low temperature radiant surfaces			■			■		■		■	■	■	■			■	■	
Night sky radiation											■				■	■		■
Ground heat exchanger								■										
Active conditioning systems																		
Heat Pump (air to air)			■	■	■									■				
Heat Pump (air to water)	■	■					■		■	■		■		■	■	■		
Heat Pump (water to water)						■		■			■					■		
CO2 Heat pump																	■	
Infrared radiant panels					■													
Absorption machine																	■	
Hot water																		
Solar Thermal panels					■		■		■	■					■			
Evacuated tubes or panels				■		■							■					■
PVT or CPVT	■	■					■	■			■			■	■	■	■	
Heat pump (as main source or backup)	■	■	■				■	■	■	■	■	■		■	■	■	■	
Other energy efficiency solutions																		
Solar thermal clothes dryer	■																	
Clothes drying (heat pump heat recovery)								■							■			
Grey water heat recovery											■					■		
Dishwasher (with Zeolite)		■											■			■		
Heat pump with dual compressors							■											
Daylighting by optical fiber											■							

■ Used (or installed). ▼ In the documentation but not used (or not installed).

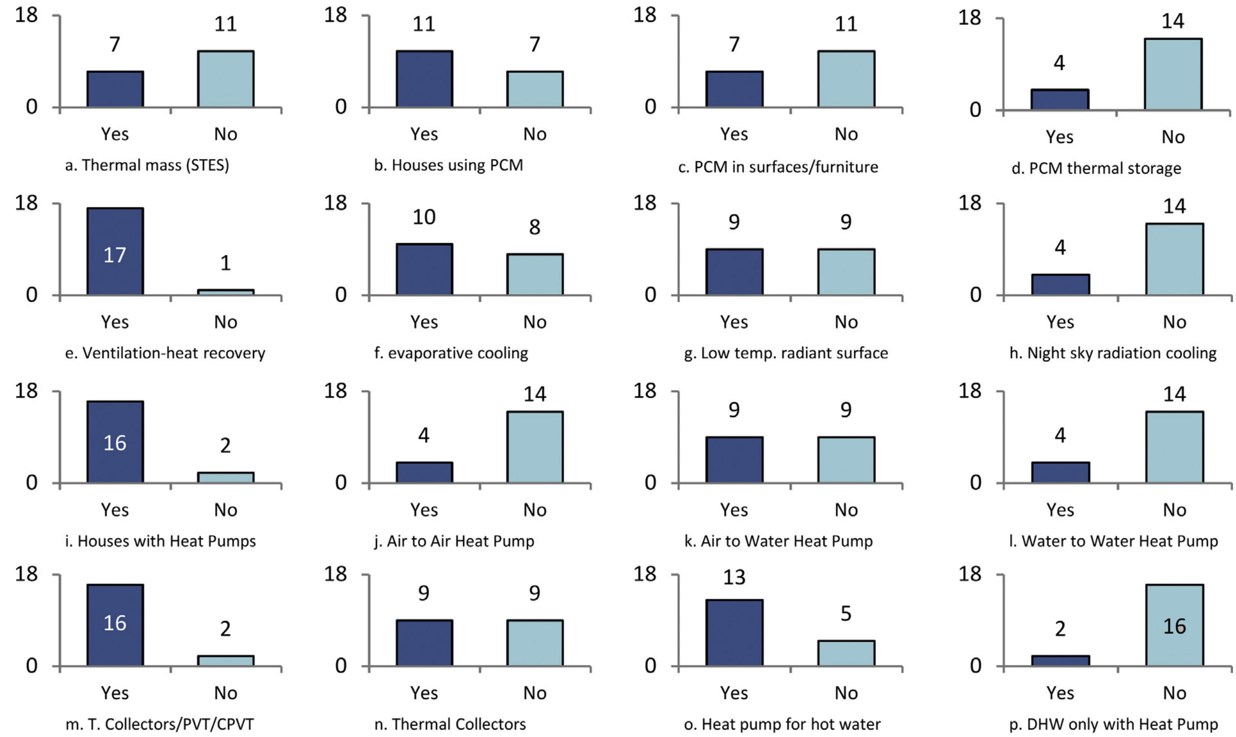


Fig. 6. Houses thermal energy storage, hybrid solutions, active conditioning and DHW systems.

- Teams make adjustments in their houses to improve their performance in the competition site but possibly their houses have a better performance in their local context.
- The houses are monitored only for twelve days. Within this period, it is not possible to determine with certainty the annual performance of the houses.
- Some aspects of the competition as the public visits affect the performance of the houses. For example, the use of thermal mass can be disturbed by the need to open the house and allow hundreds of people who enter every day.

Due to the limitations of evaluating the houses based on the monitored data, it is necessary to obtain experts' advice. These experts are the Competition Juries. In the next sections, the assessment of the Energy Efficiency Jury will be analyzed.

5. Energy Efficiency Jury evaluations

In this section, the information related to Energy Efficiency Jury evaluation is presented. This information is based on the Energy Efficiency Jury Evaluation Reports and the chapter of the SDE 2012 book written by one of the jury member [22]. It is important to point out that the Energy Efficiency evaluation was carried out taking into account of the local contest as well as the described concept for the after competition use.

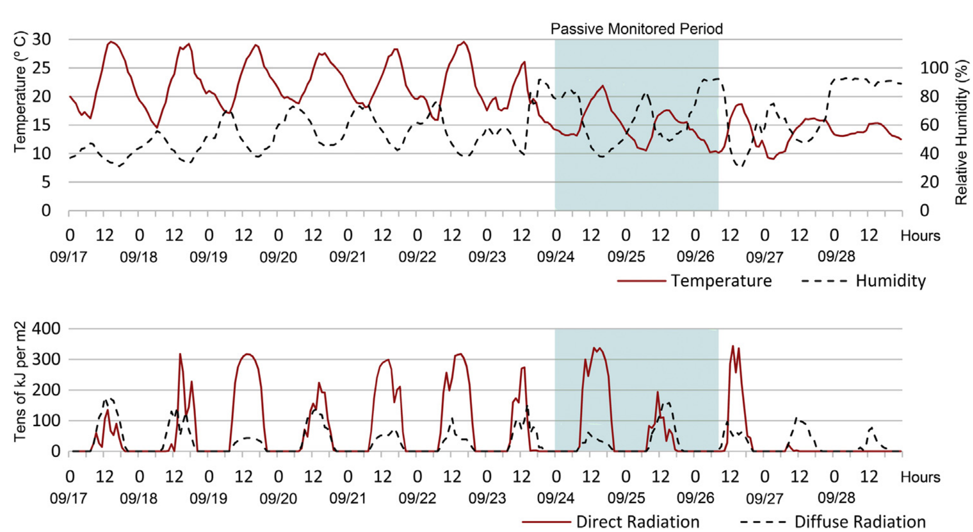


Fig. 7. Climatic conditions during the SDE2012 monitored period.

Table 2
Ideas extracted from the jury evaluation reports.

Positive elements found by the jury	Aspects that need to be improved in some houses
Envelope - Thermal envelope. The highly insulated opaque building envelope – vacuum thermal insulation panels – thermal break elements - Glazing. Different triple pane glazing is applied in high quality frames – vacuum insulation – Special glass – Air tightness	Envelope - The *U* value of the opaque walls is a bit too high, same as the amount of glass - Concerning the effectiveness of the outer skin to reduce the thermal stress (high infiltration rates in winter, uncomfortable air flow in summer or uncomfortable temperatures caused by stack effect ventilation - Sliding doors causing large infiltration rates). - Large amount of glass - The lower air tightness created by the use of sliding windows
Passive systems - Glass sizes, orientations and solar protection to maximize the gains in heating periods and avoid the overheating in cooling periods. - Ventilation, natural ventilation – natural ventilation can be achieved quickly and efficiently - Sky is used for passive cooling	Passive systems - Natural ventilation was achieved with some doubts - No real ventilation concept.
Thermal storage energy - PCM tanks for the heat pump - Thermal storage in the active system (heat pump) assists to reduce the power peaks - Cooling ceiling with a combination of water and paraffin-wax PCM	
Hybrid solutions - High efficiency heat exchanger in the ventilation system - Surface heating/cooling system - Good solution for forced night ventilation - Night cooling of the ceiling is achieved by circulating water between the external storage and a hybrid element cleverly designed, whereby the clay roof is discharged and available for the next day. - Heating and cooling were provided using inertia tanks and thermal mass. - Low temperature surface heating/cooling system - Clever solutions of (e.g. evaporative adiabatic cooling facade)	Hybrid solutions Some proposed solutions present problems related with their durability and maintenance
Active systems - High efficient HVAC - Strategies to increase the efficiency of the HVAC system, including the use of thermal storage systems - Use of active system based on or complemented with sensible and latent thermal energy storage - High efficiency appliances, pumps and other equipment	Active system - Partly non efficient devices - Incorrect selection of pumps and controls may cause high consumption
Hot water - Efficient hot water systems - Innovative solar systems used - PV and thermal hybrid systems.	
Daylight - Daylight solutions that reduce the energy consumption and enhance the interior comfort.	
Control system - Advanced building automation control system (BACS), user friendly and easy understand displayed information	

Juries first assessed the design strategies to reduce the energy demands, and then evaluated the active systems selected to reduce the energy consumption. An appropriated balance between passive and active solutions was assessed positively.

The jury said that the evaluation was not only centered in the energy aspect but also in the capacity of the houses to offer a liveable spaces in which all the necessary activities can be carried out and a healthy and high quality indoor environment. They appreciate the effort of some teams to produce most passive houses, and the innovative solutions related to the enhancement of the interior comfort and the reduction of energy consumption. Additionally, they pointed out that the teams have done a good contemporary re-interpretation of their country vernacular architecture and its passive strategies. One of the jury wrote: “some designs are inspired by their local traditional buildings, not a return to heritage and tradition, but using them as a foundation” [22].

In relation with the jury findings, one of them wrote “Teams demonstrated an extremely high level of energy efficiency in their house design and its technical systems, components and materials as well as appliances, each contributing to the final integrated value of energy efficiency of the house. Their approach to the HVAC systems design was thoughtful and creative with the concept selection, sizing and resolution of the HVAC systems facilities, and evaluation and optimization of passive and active strategies – searching for the most energy efficient combinations. In addition, it is important to stress, that all teams in their search for energy efficiency did not neglect the broader requirements of the house, particularly indoor air quality and all other aspects of the indoor environment quality” [22]. Table 2 shows some ideas related with the energy efficiency of the participating houses, extracted from the jury evaluation reports.

6. Energy Efficiency assessment and houses' performance in the competition

Given the characteristics of SDE competition, the energy efficiency should have a significant impact in the performance of the participating houses in the overall results as well as in the contest that are related with this topic. In Section 2, it was explained that the Energy Efficiency Contest is closely related to other juried and monitored contests. In the followings sub-sections, comparative studies of the Energy Efficiency Jury evaluation and the results in other areas of the SDE 2013 competition are included.

6.1. Energy efficiency and the overall results

SDE 2012 Energy Efficiency Jury conceded the first five places to eight houses. These houses earned between 100 and 80 percent of points in this category, see Fig. 8. On the final results, these houses were also on the first eight positions. The house that got the first prize in Energy Efficiency also got the second prize in the competition. Similarly, the houses that received the first and third prizes were tied in the fourth position of the Energy Efficiency evaluation. It can, therefore, be concluded that certainly the energy efficiency houses won the competition.

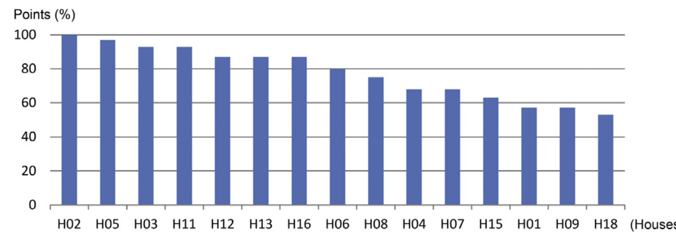


Fig. 8. Houses ranking based on the points earned in the Energy Efficiency Contest.

6.2. Energy efficiency and other related juried contests

As explained in Section 2, some aspects related with the Energy Efficiency have also influenced the evaluation of other juried contest such as Architecture, Engineering and Construction and

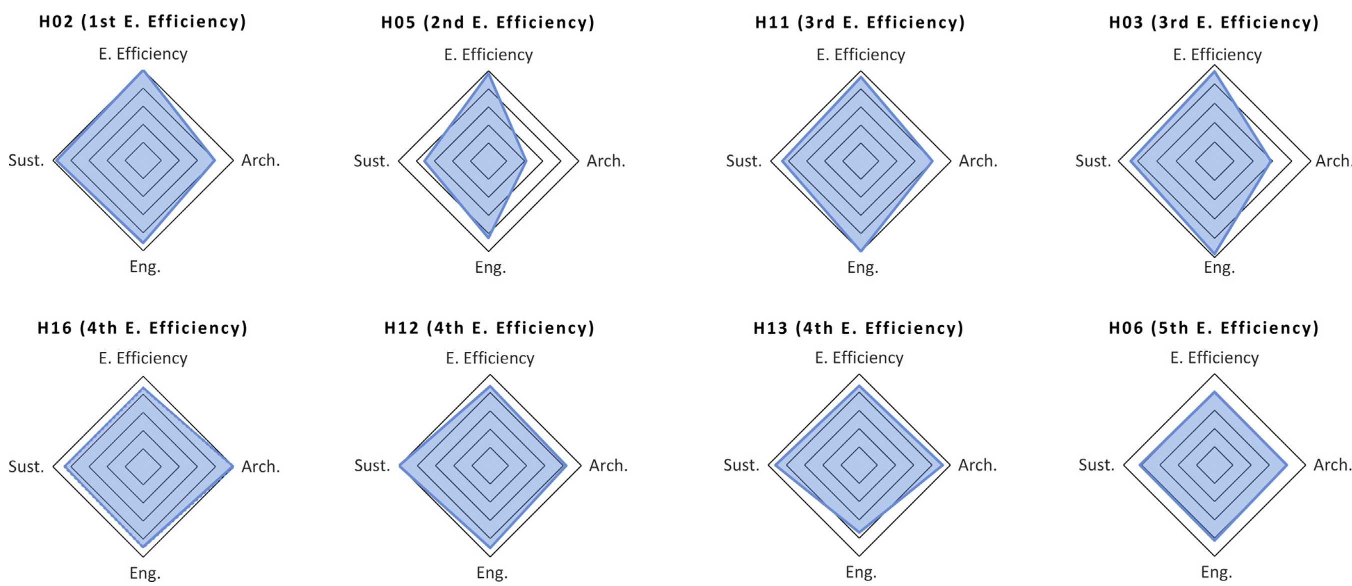


Fig. 9. Energy efficiency results versus other related juried contests.

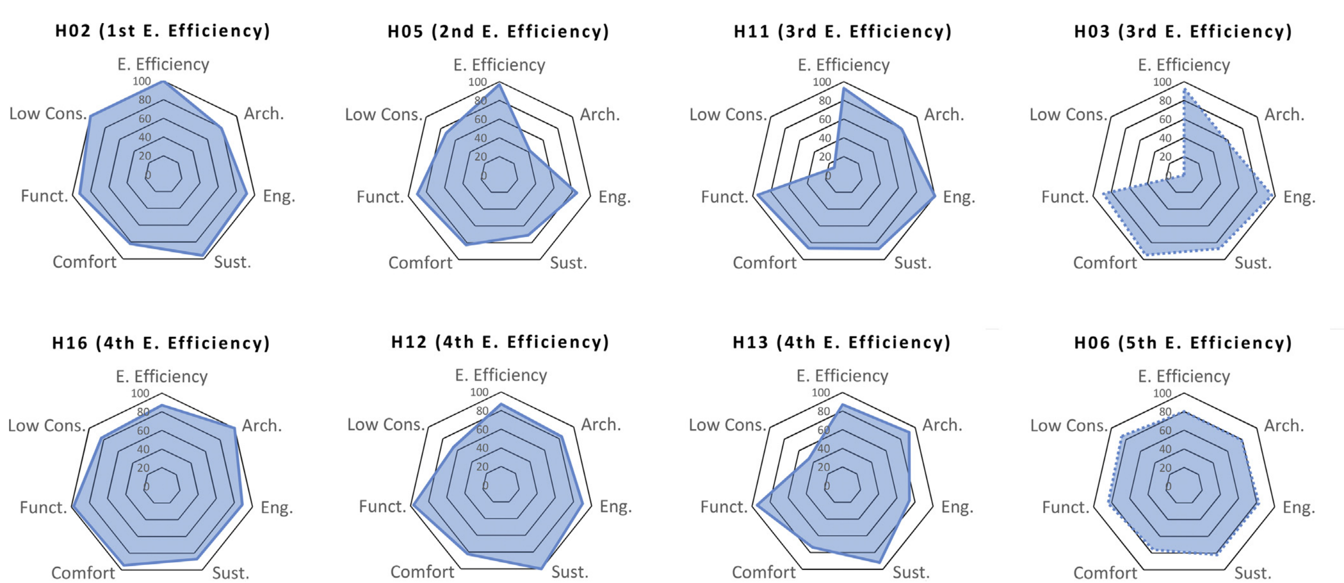


Fig. 10. Energy efficiency results and other related contests.

Sustainability. The eight houses in the first five positions of Energy Efficiency were used to illustrate the relation between this contest and other juried ones. As shown in Fig. 9, there are good agreement between Energy Efficiency and the Engineering evaluation. The three first places in Engineering (H11, H03 and H02) were also in the three first places of Energy Efficiency. Additionally, the same houses are in the first seven positions of these both contests. There was also a good agreement between the evaluation of the Energy Efficiency and Sustainability assessment. In the SDE 2012, five of the houses that were between the first and fourth position in Efficiency were also in the seven best places of the Sustainability Contest. Similarly, the six best houses in Architecture Energy Efficiency were also in the first eight of Energy efficiency. However, as shown in Fig. 9, the houses H05 and H03 obtained the second and third position in Energy Efficiency but they do not get high grades in Architecture.

6.3. *Energy efficiency and other monitored contest*

Before starting the presentation of the comparative study between the Energy Efficiency Jury assessment and house performance during the monitored period, it is necessary to indicate that the measurement results were not known at the time of jury evaluation and to highlight the differences between these evaluations. The monitored evaluation gives information of the houses performance in the environmental conditions of the monitored period. These environmental conditions might be different from the houses permanent conditions. Similarly, the houses consumption is related with the competition tasks requirements. The frequency, and the times, in which these tasks will be performed in their permanent house location is different. Another limitation of the monitoring information is the limited time, twelve days.

On the other hand, as was explained for one of the Jury, they evaluated the houses based on their expected performance in their permanent location. This evaluation takes into account the environmental conditions of the houses permanent location. Jury assessment is based on the documentation submitted by the Teams and the visits to the houses. Complete and precise documentation help the jury to get a better understanding of the houses' strategies and their energy performance in their local context. Therefore, teams' capacity to communicate their projects might affect the result of the Jury assessment.

Additionally, the monitored performance is influenced in the occupant's behavior. The occupant's actions have a significant impact in the buildings consumption. Fig. 10 summarizes the results of the energy efficiency assessment in relation with the related juried and monitored contest.

6.3.1. *Energy Efficiency Jury' assessment and Comfort Conditions results*

Energy efficiency is not in conflict with the comfort conditions; on the contrary one of the challenges of the energy efficiency building is to maintain the interior comfort using a minimum of energy. Fig. 11 shows the relation between the evaluation of the Energy Efficiency Jury and the interior comfort conditions during the monitored period. In this figure only the values of dry bulb interior temperature, humidity and air quality were taken into account.

The SDE 2012 requirements in terms of comfort temperature are very strict and, in some occasions, it is difficult for most-passive houses to get high punctuation. In the analysis of the results, it was found that six of the eight houses with higher punctuation in Comfort Conditions were in the first fifth position in the Energy Efficiency Jury. However, the first and second places in Energy Efficiency were not in the houses with the higher position in The Comfort Conditions Contest.

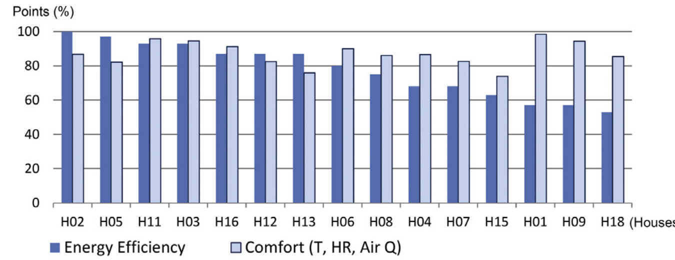


Fig. 11. Energy efficiency and comfort conditions (dry bulb temperature, relative humidity and air quality).

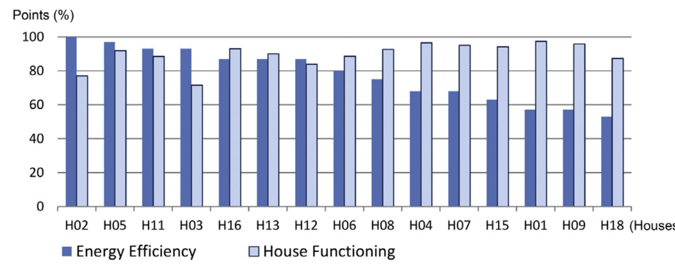


Fig. 12. Energy efficiency and house functioning.

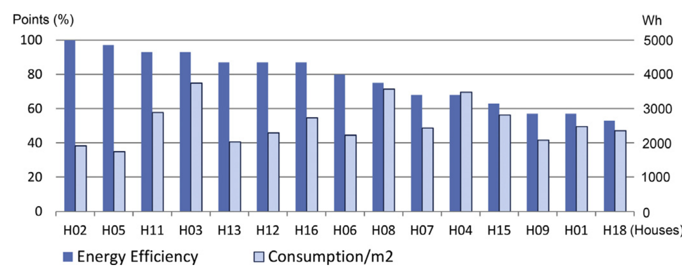


Fig. 13. Energy efficiency and electrical energy consumption per square meter (during the whole monitoring period).

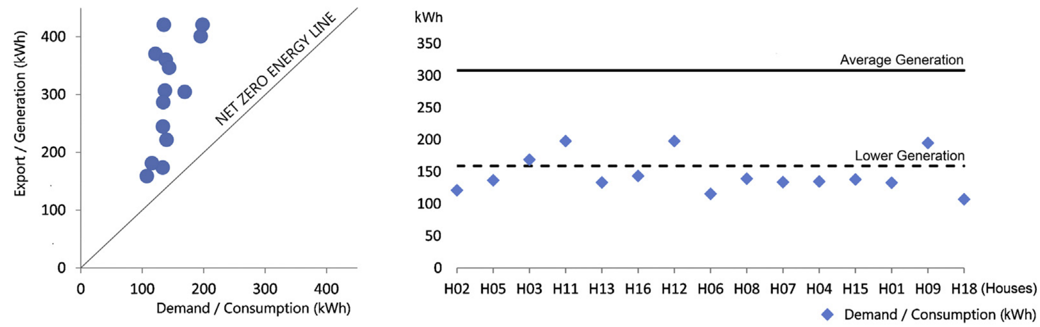
6.4. *Energy Efficiency and House Functioning Contests results*

In Section 2.3.2, the House Functioning Contests was explained. Every day team members have to perform all the required tasks following the competition calendar. Fig. 12 shows the relation between the Energy Efficiency Jury assessment and the House Functioning Contest results. As shown in this figure, there are no correlation between the Energy Efficiency Jury and the House Functioning results.

6.5. *Energy Efficiency Jury' assessment and consumption per m^2 results*

The final objective of the energy efficiency is to reduce the energy consumption. In the competition, the consumption of the houses is monitored continuously and at the final this consumption is related with the net area of the house. The house with less consumption wins the Energy Consumption per m^2 Contest. Fig. 13 shows the relation between the Energy Efficiency Jury assessment and the energy consumption during the monitored period. As was previously clarified, the consumption during the competition is related with the environmental conditions of the monitoring period and the tasks required in the competition calendar. The value of this contest is not directly related with the real consumption of the houses in their permanent location.

H02, H06, H16 and H05 obtain the four best positions on the Energy Efficiency Contest. And, they were also the houses with



a. Electrical Energy Balance

b. Comparison of demanded energy and generated energy

Fig. 14. Energy consumption versus energy production (during the monitored period).

less energy consumption during the competition. However, most of these houses were not at the top places of other monitored contests. The exception was H16, which obtained a remarkably good position in all three monitored contests related to energy efficiency. This house had a low-energy consumption (the fourth lowest), and won the first place in House Functioning. It also won the third prize in Interior Comfort.

Moreover, the Energy Efficiency Jury assigned to H15 the eighth position behind the first eleven houses. However, this house had a good performance in the monitored contests, first place in Interior Comfort, third in Functioning House and eighth in Consumption per Measurable Area, consuming less than four of the houses most valued by the jury of energy efficiency.

6.6. Energy efficiency assessments and the energy zero building challenge

Certainly to be an energy efficient building, it is not needed to generate energy. Energy efficiency is mostly related to the reduction of the energy consumption. However, the first requirement stated by the recap EPBD is to be high efficient building, and being the case studies solar houses, it is fundamental to know if these houses qualify to be called zero energy buildings. This analysis was carried out in two different scenarios: energy balance on-site (during the monitored period) and predicted annual energy balance. The SDE houses are all-electric buildings. This simplifies the energy balance equation since it is not needed weighting factors for the calculation; electricity is the only energy supplied and demanded. For this reason, the contest related with monitored energy performance is called electrical energy balance.

6.6.1. Electrical energy balance during the monitored period

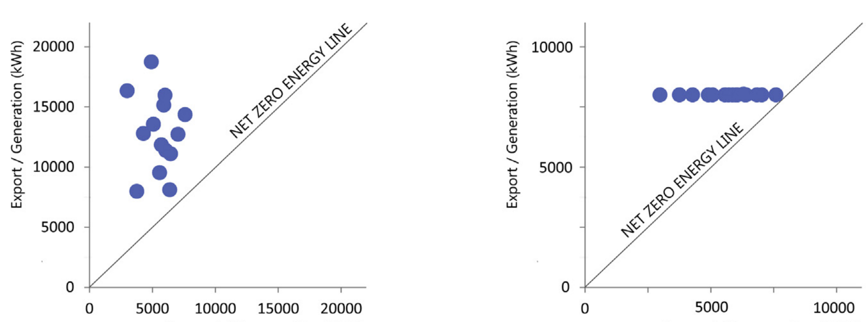
The energy consumption of the houses during the twelve days of the competition was greater than their regular consumption, since the competition required an intensive use of hot water and appliances (such as ovens, washing machines and dishwashers). Even so, the fifteen houses analyzed had a positive balance during the competition period as shown in Fig. 14a. During the monitored period, the average consumption of the houses was 146 Wh, being the highest consumption 198 Wh. In terms of energy production, the average electrical energy production was 208 Wh, and the highest production was 421 Wh [14]. Dots in the Fig. 14b represent the energy required for the houses, the dashed line represents the energy that was produced by the house with the smallest PV installation and the continuous line represent the average of energy that was produced by the houses. This figure shows that, in the hypothetical case in which the electrical energy generation of all the houses would have been equal to the lowest one, most of them would continue having a positive balance during the competition period.

Fig. 14 shows the result of the comparative study of the energy consumption of these houses with the production of the smaller PV array presented in the SDE 2012, as well as with the average production during the monitoring period.

6.6.2. Predicted annual electrical energy balance

The monitored period are not enough to determining the energy performance of the houses or their energy balance.

For the annual energy analysis, the energy simulation carried out by the participating teams was used. The results of these simulations provide an annual estimation of houses energy demand and generation. As Fig. 15a shows, all the studied houses qualify



a. Annual energy balance calculation using the houses' estimated consumption and generation.

b. Hypothetical annual energy balance calculation using the houses' estimated consumption and the generation of the smallest PV array.

Fig. 15. Annual predicted energy balance.

to be classified as Plus Energy Buildings, provided that their final energy balance coincides with the estimated values. Indeed, being grid-connected houses, they could be classified as Net Plus Energy Buildings [23,24]. An additional hypothetical possibility was also analyzed. Do all the houses be Energy Plus Buildings having the same small energy generation as the house with the smaller PV array? As shown in Fig. 15b, all the fifteen houses continue being Net Plus Energy Buildings. This is possible since all the studied houses are low energy buildings.

6.7. Recommendations for future competitions (how this recommendation affect the energy efficiency assessment)

While this research was carried out, it was found some elements in the SDE 2012 competition that need to be re-thought. Some of them are related with the possibilities to enhance the use of passive and hybrid solutions; others are related with get a better analysis of the houses energy performance.

Recommendation regarding passive and hybrid systems:

- Take into account the radiant temperature, evaluating the operative temperature and not only the air temperature.
- When the competition is held during the summer, used the adaptive comfort in state of fixed comfort bands, Additionally, evaluated the possibility to have a different criteria to evaluate the temperature during the nights, using a lower temperature in the assignation of points and avoiding penalizing the use of night ventilation.

Recommendations regarding houses energy performance:

- Install additional power meters to monitor independently the HVAC/DHW consumption. These meters will register the consumption related with the house conditioning in both passive and regular monitored periods.
- Determinate the energy consumption in the local context of the houses (total and related with HVAC/DHW), in order to verify their improvement in energy efficiency.
- Limit the energy consumption of the hybrid systems during the passive monitored period. In this period, it is also needed that interior lighting levels being monitored. It is fundamental that the houses get a correct balance between the sun protection and the daylight possibilities.

7. Conclusions

Energy efficiency buildings are characterized by a good balance between passive strategies (means to minimize the energy demand), and high efficiency equipment (means of reduce the consumption). The goals of the first Energy Performance of Buildings Directive (EPBD) are closely related with these very low energy buildings. Also, the goals of the recast EPBP in relation to near to zero energy buildings are based on this kind of buildings.

In this paper, fifteen houses that participated in the Solar Decathlon Europe 2012 (SDE 2012) were used as case studies. The SDE has been successful in extending the understanding of sustainable construction and the importance of passive and solar design strategies to university students, professionals and the general public. Its rules emphasized the reduction of energy consumption in buildings, the increment of energy efficiency in buildings and the need to cover the energy demanded to a very significant extent with energy from renewable sources produced on-site.

The studied houses include many passive design strategies as well as energy efficiency systems and equipment. This paper includes a review of these solutions. It also includes a comparative study between the Energy Efficiency Jury evaluation and the measured performance of these houses in the competition. Many of the houses achieved an excellent balance between passive strategies (envelope, orientation, heating and cooling strategies) and high efficiency active systems. These design decisions help them to maintain houses hydrothermal comfort and do all houses regular tasks with minimum energy consumption. This low consumption permits that all of them obtained a positive energy balance in both in the annual energy simulations and on-site during the monitored period. If their energy performance, once placed in their permanent location, is similar to the predicted one, all of them will qualify to be Plus Net Energy Buildings.

Additionally, some recommendations that can help to get a better understanding of the participating houses energy efficiency were identified. In relation with the comfort conditions, it was recommended to take into account the radiant temperature, evaluating the operative temperature and not only the air temperature. In the summer, competition used the adaptive comfort in state of fixed comfort bands, and permits the lower temperatures in the night hours to do not penalize the use of night ventilation. Related with energy consumption, a power meter needs to be installed in order to monitor independently the HVAC consumption. Also, should be good to have references about the energy consumption (total and in HVAC) in the participating houses local context in order to verify their improvement in energy efficiency. Finally, for the passive monitored period, the consumption of the hybrid systems should be limited, and the lighting level during this period is monitored continuously.

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